Journal of Hydrology 561 (2018) 444–460

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses

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ARTICLE INFO

Article history:
Received 25 January 2017
Received in revised form 21 November 2017
Accepted 23 November 2017
Available online 24 November 2017
This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Sankar Arumugam, Associate Editor

Keywords:
Irrigation
Model
Agriculture
Hydrology
Climate change

ABSTRACT

Irrigation efficiency plays an important role in agricultural productivity; it affects farm-scale water demand, and the partitioning of irrigation losses into evaporative and non-evaporative components. This partitioning determines return flow generation and thus affects water availability. Over the last two decades, hydrologic and agricultural research communities have significantly improved our understanding of the impacts of climate change on water availability and food productivity. However, the impacts of climate change on the efficiency of irrigation systems, particularly on the partitioning between evaporative and non-evaporative losses, have received little attention. In this study, we incorporated a process-based irrigation module into a coupled hydrologic/agricultural modeling framework (VIC-CropSyst). To understand how climate change may impact irrigation losses, we applied VIC-CropSyst over the Yakima River basin, an important agricultural region in Washington State, U.S. We compared the historical period of 1980–2010 to an ensemble of ten projections of climate for two future periods: 2030–2060 and 2060–2090. Results averaged over the watershed showed that a 9% increase in evaporative losses will be compensated by a reduction of non-evaporative losses. Therefore, overall changes in future efficiency are negligible (−0.4%) while the Evaporative Loss Ratio (ELR) (defined as the ratio of evaporative to non-evaporative irrigation losses) is enhanced by 10%. This higher ELR is associated with a reduction in return flows, thus negatively impacting downstream water availability. Results also indicate that the impact of climate change on irrigation losses depend on irrigation type and climate scenarios.

1. Introduction

While meeting agricultural water demand has already been a challenge in many parts of the world (e.g., Andreadis and Lettenmaier, 2006; Elsner et al., 2010; Mann and Gleick, 2015), stressors such as climate change can significantly exacerbate water-related threats to the sustainability of agricultural production (Lobell and Burke, 2009; Trenberth et al., 2014; Wallace, 2000). Climate change is expected to modify water and energy cycles through increases in air temperature and by changing seasonal and temporal precipitation patterns (Adam et al., 2009; Hamlet and Lettenmaier, 1999; Seneviratne et al., 2010; Stewart et al., 2004). These changes are expected to impact crop water demand (Tao et al., 2003; Wada et al., 2013; Yorgey et al., 2011), irrigation water availability, and agricultural productivity (Elliott et al., 2014; Wada et al., 2013). Due to the importance of agriculture for sustaining human needs, this research area has attracted significant attention (e.g. Anwar et al., 2013; Elliott et al., 2014; FAO, 2003; Kurukulasuriya and Rosenthal, 2013). However, although many researchers have analyzed the potential impacts of future climate on different aspects of agriculture, to the best of our knowledge the impacts of climate change on irrigation efficiency and the partitioning of irrigation losses have not been studied. At the farm level, irrigation efficiency is important for productivity especially during drought years, and improvement in irrigation efficiency (e.g., through new technology) is considered to be an adaptation strategy for more frequent droughts (Berbel and Mateos, 2014; Heumesser et al., 2012). However, investment in new irrigation technology or managing the system more efficiently may not have the same impact in a future climate as it did historically. Climate change can affect not only the overall efficiency of irrigation systems, but also the partitioning of irrigation losses between non-evaporative and evaporative components. This partitioning is important for determining how much of the applied irrigation water is lost to the atmosphere (i.e., consumed) versus returns to the system for reuse by downstream irrigators.

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https://doi.org/10.1016/j.jhydrol.2017.11.046
0022-1694/© 2017 Published by Elsevier B.V.

Nomenclature

g	acceleration of gravity	LAI	leaf area index
ET_a	actual evapotranspiration	MAD	maximum allowable depletion
$\Delta\theta$	change in soil water content	ET_p	potential evapotranspiration
Y	canopy height	b_i	runoff calibration parameter
DP	deep percolation	K_s	saturated hydraulic conductivity
D	droplet size	ρ_b	soil bulk density
q	emitter discharge	$\varnothing$	soil porosity
DP	deep percolation	θ_{fc}	soil water content at field capacity
E_c	evaporation from intercepted water	θ_{pwp}	soil water content at wilting point
E_d	evaporation from irrigation droplets	θ_{WC}	soil water content of top soil layer
E_s	evaporation from soil	SWD	soil water deficit
E_{si}	evaporation from soil during irrigation	A_w	soil wetted area
GDD	growing degree days	S	sorptivity coefficient
Y_0	height of nozzle	t_{irr}	time of irrigation
V_0	initial velocity of droplets	T	transpiration
$ESTS$	irrigation evaporative loss after irrigation	D_s	VIC base flow calibration parameter
ISC	irrigation system capacity	Ds_{max}	VIC base flow calibration parameter
ITF	irrigated transpiration fraction	W_s	VIC base flow calibration parameter

The objective of this study is to quantify how different irrigation loss components and overall irrigation efficiency are affected by climate change. In this study, we first describe the incorporation of a mechanistic irrigation module into a land surface model that captures the interactions between hydrology and crop growth, phenology, and management (VIC-CropSyst). Then we use this tool to investigate the impacts of climate change on future irrigation requirements and overall efficiency. We also analyzed how future climate affects watershed-level water availability through modification of the partitioning of overall irrigation efficiency into evaporative and non-evaporative loss fractions. We conclude with discussion on how this may impact water availability for downstream water users.

2. Background

2.1. Climate change impacts on irrigation efficiency

While new irrigation technology and management strategies are traditionally optimized to increase overall irrigation efficiency, systems-level thinking suggests that irrigation systems should be managed to optimize water availability for agricultural production at the watershed level, e.g., by considering downstream in addition to field-level water availability (Allen et al., 2005; Wallace, 2000; Willardson, 1985). Climate change may modify the efficiency of irrigation systems in a number of ways: 1) through potential evapotranspiration (ETp), 2) soil moisture, and 3) crop biomass. Each of these is described below in further detail.

2.1.1. Potential evapotranspiration

Warming is expected to increase ETp (Chaouche et al., 2010; Douville et al., 2013; Goyal, 2004; Hamlet et al., 2007), resulting in the potential to increase evaporative losses and reduce overall irrigation efficiency.

2.1.2. Soil moisture

Climate change impacts soil moisture through modifying ETp and the seasonality and magnitude of precipitation (Dorigo et al., 2012; Holsten et al., 2009; MacDonald et al., 1994; Seneviratne et al., 2010). Altered soil moisture modifies soil hydraulic properties (McCuen et al., 1981; Rawls and Brakensiek, 1989; Youngs, 1968) that affect the generation of runoff and deep percolation losses. For example, when the soil surface is drier, suction head is higher; this increases the infiltration rate which leads to lower runoff loss. Changing soil water content also impacts hydraulic conductivity, which modifies the water movement in the soil and affects deep percolation losses.

2.1.3. Crop biomass

Crop biomass affects irrigation evaporative losses through modification of interception capacity (and thus through evaporation of water on the leaf surface) and through changes in canopy coverage (affecting bare soil evaporation). Crop biomass also affects transpiration, but we do not define transpiration as an irrigation loss as it is a necessary process related to crop growth. Climate change impacts biomass production in many ways. Elevated CO_2 concentrations usually have a positive impact on photosynthesis and improve the yield (Lobell and Field, 2008; McGrath and Lobell, 2013). Higher temperatures can have either positive or negative impacts; in colder climates, warming provides more energy for crop growth, resulting in improved productivity and more biomass (Linderholm, 2006; Menzel and Fabian, 1999), while in many other regions higher temperatures shorten the growing season relative to a specific crop (i.e., crops may go through their phenological stages faster under warmer conditions) and reduces time available for photosynthesis with potentially negative impacts on crop growth (Craufurd and Wheeler, 2009; Eitzinger et al., 2013). Extreme water and heat stress can also negatively impact crop biomass production (Deryng et al., 2014; Mann and Gleick, 2015; Nam et al., 2015; Siebert et al., 2014).

2.1.4. Combined effects

Irrigation losses are interdependent; this adds complexity to the assessment of the impact of climate change on irrigation efficiency. For each individual irrigation droplet, evaporation losses happen when water is exposed to air; the remaining water may be lost to runoff generation or may infiltrate into the soil and can be lost either through transpiration (which benefits the crop) or deep percolation (which does not). Therefore, any alteration of the climate will affect all loss components simultaneously both directly and indirectly due to inter-relationships between these components. Evaluation of these complex relationships requires models that include mechanistic representation of each of the irrigation loss components and their interdependencies.

2.2. Watershed-level impacts of changing irrigation efficiency

How irrigation losses are partitioned at the watershed level is important because runoff and deep percolation, which together are usually referred to as non-evaporative or non-consumptive irrigation losses, can generate reusable return flows. In many agricultural areas, irrigation return flows play an important role in the availability of water for downstream water users (Allen et al., 1996; Howell, 2001; Maréchal et al., 2003; Pfeiffer and Lin, 2014). Any changes in infiltration, plant uptake, and transport processes of irrigation water modify the quantity and quality of return flow (Burt et al., 1997; Causapé et al., 2004; Tanji, 1981). Because climate change can impact the ratio of evaporative (i.e., consumptive) water use to non-evaporative losses, it can potentially change both the magnitude and timing of return flow and watershed-level water availability. Capturing the complex impacts of climate change on irrigation losses at the watershed-level requires a spatially-distributed simulation platform appropriate for larger scales that captures the interconnections between the hydrologic cycle, irrigation technology and management, and crop growth, phenology, and management. However, in the current state of large-scale hydrologic and agricultural modeling, irrigation losses are either ignored (e.g. Sacks et al., 2009, Leng et al., 2013) or prescribed with a fixed fraction (e.g. Haddeland et al., 2006; Pokhrel et al., 2011). Herein, we describe and apply a new mechanistic irrigation module as a component to a coupled hydrologic and cropping systems model.

2.3. Study domain: Yakima River basin (YRB), Washington State, U.S.

Irrigation return flow is important for many agricultural river basins of the Western U.S. (Bliesner et al., 1977; Tanji, 1981; USBR, 2010) and many of these basins are susceptible to warming-induced loss of snowpack which stores winter precipitation for use during the irrigation season (Hamlet et al., 2007; Mote et al., 2005; Stewart et al., 2004). Therefore, changes in irrigation loss components can exacerbate water stress in some watersheds if they result in a reduction of return flow. To understand the impacts of climate change on irrigation efficiency and regional water availability of the western U.S., we conducted a case study over the Yakima River Basin (YRB), located in the state of Washington (Fig. 1). Agriculture is an important component of the basin's economy with approximately 1.7 billion dollars of annual income based on yield reported by the National Agricultural Statistical Service (NASS) in year 2012. Although the YRB regularly experiences droughts (USBR, 2012), the frequency and severity of future droughts are expected to increase as a result of climate change (e.g., Elsner et al., 2010; Vano et al., 2010; Yorgey et al., 2011). Moreover, water availability for irrigation in the YRB depends on the timing and magnitude of return flows from inefficiently irrigated areas (see Fig. 1 for the location of the major irrigation districts within the YRB and Fig. 2 for the percentage of land irrigated by each technology). In general, YRB irrigation efficiency is not very high; about 70% of the basin is irrigated through surface and sprinkler systems with significant return flows. The United States Bureau of Reclamation (USBR) estimated that return flow is the source of more than 40% of mid-summer water availability in the region (USBR, 2002). Therefore, the impact of climate change on the partitioning of irrigation losses between evaporative and

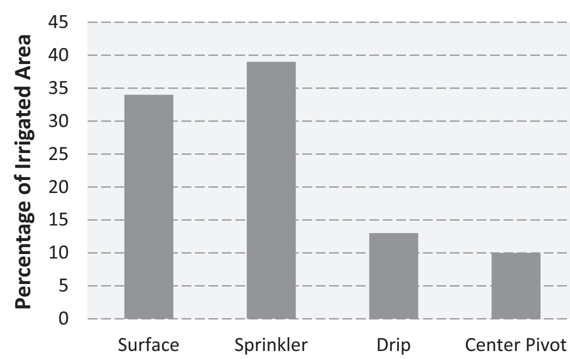

Fig. 2. Irrigation systems in the YRB (USBR, 2010). The bars show what percentage of the total basin's irrigated agriculture is irrigated with each system.

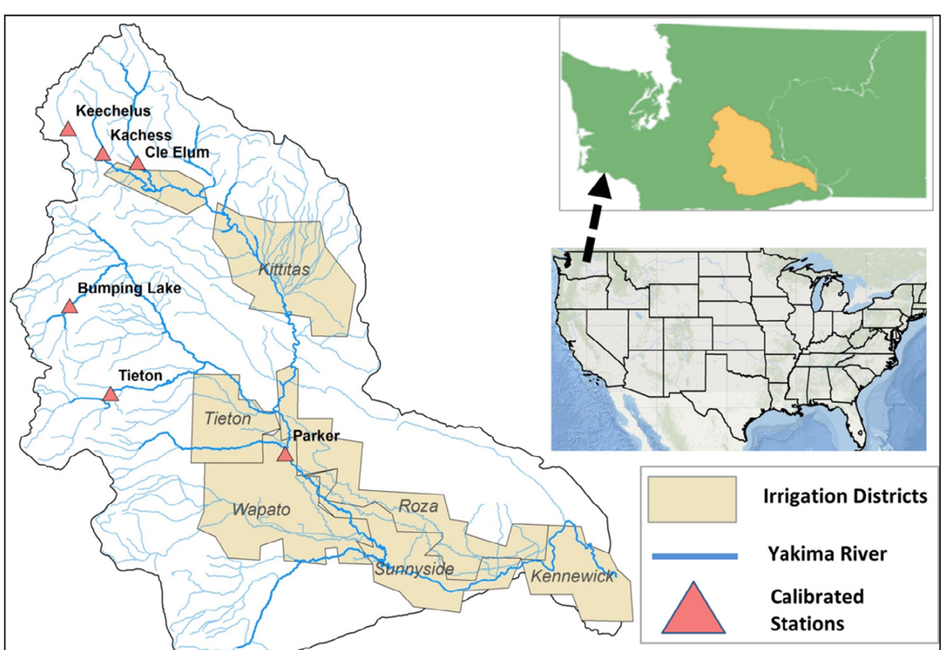

Fig. 1. Map of the Yakima River Basin (YRB) in Washington State of the U.S. (see inset), including the boundaries of six major irrigation districts located in the YRB, and streamflow stations used to calibrate our model (VIC-CropSyst).

non-evaporative components can potentially play an important role in defining future water availability in the YRB.

3. Methods and data

3.1. Simulation tools

A computational modeling platform that captures the complexities in the interactions between the hydrologic cycle, crop growth and phenology, and crop and water management is required to evaluate the impact of climate change on irrigation efficiency. There is a limited number of studies that focus on mechanistic simulation of irrigation losses in large-scale hydrologic models. To create such a platform, we developed a mechanistic irrigation model that can simulate the impacts of climate, soil moisture and irrigation management on irrigation efficiencies and losses. The irrigation module was implemented in VIC-CropSyst (Malek et al., 2017), a physically based hydrologic-agricultural model. This section describes the modeling tools used in this study.

3.1.1. VIC-CropSyst

The framework of the VIC-CropSyst (Fig. 3) model is explained by Malek et al. (2017). In the coupled model, VIC balances the energy and water budgets, e.g., through simulation of hydrologic components such as soil hydrology, runoff, base flow, ETp, and snow. VIC passes the available energy for transpiration and soil water content in different layers to CropSyst which uses this information to calculate transpiration, biomass accumulation and other crop processes. Finally, VIC uses the transpiration provided by CropSyst to update the vertical soil moisture distribution and other hydrologic processes such as runoff and baseflow. Therefore, while VIC-CropSyst includes the large-scale capabilities of the VIC model in the simulation of hydrologic processes, it uses CropSyst to simulate agricultural processes; therefore VIC-CropSyst is an integration of farm- and regional-scale processes. Malek et al. (2017) tested VIC-CropSyst at two flux tower sites in the states of Illinois and Nebraska in the U.S. and found reasonable agreement between simulated and observed irrigation water, evapotranspiration, leaf area index and soil moisture. The authors also performed a regional evaluation of ETp simulation over the U.S.'s Pacific Northwest region and showed that including CropSyst within the VIC model resulted in an improvement of ET simulation over agricultural landscapes.

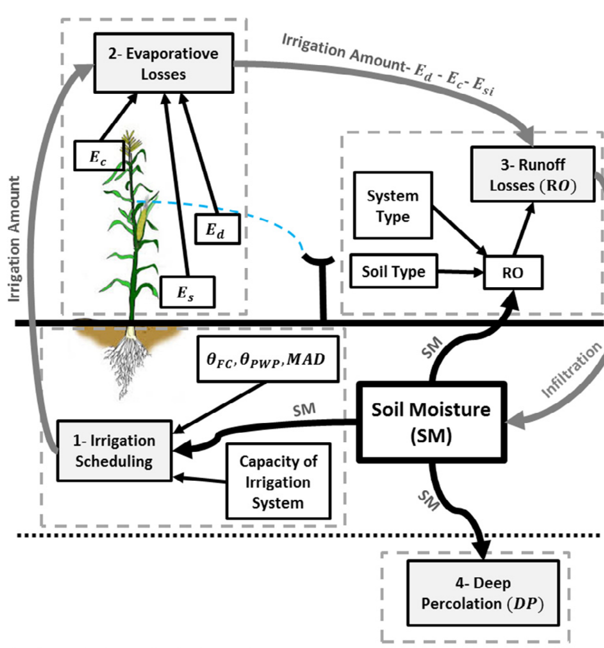

Fig. 3. VIC-CropSyst irrigation module's workflow. The irrigation module has four parts that simulate the following irrigation processes consecutively: 1) irrigation scheduling, which calculates the start time and total amount of irrigation based on soil and irrigation system characteristics, 2) irrigation evaporative loss, which calculates evaporation from canopy-intercepted water (E_c), irrigation droplets (E_d) and wetted soil (E_s), 3) irrigation runoff, which simulates the runoff loss based on soil and irrigation types and 4) deep percolation, which simulates how much of the applied water has percolated below the root zone.

3.1.2. Variable infiltration capacity model

The Variable Infiltration Capacity (VIC; Liang et al., 1994) model is a physically-based hydrologic model that simulates the cycles of water and energy for individual grid cells across a landscape. VIC has been continuously modified to improve the simulation of key hydrologic processes (e.g., Bowling et al., 2004; Cherkauer et al., 2003; Cherkauer and Lettenmaier, 1999; Liang et al. (1996); Liang et al., 1994). VIC is a large-scale model that has been applied at different scales from regional (e.g., Elsner et al., 2010) to continental (e.g., Maurer et al., 2002) and global (e.g., Adam et al., 2009). Model resolution usually varies from 1/16th° (e.g., Elsner et al., 2010; Vano et al., 2010) to 2° (e.g., Nijssen et al., 2001). Despite the large-scale nature of VIC, it is able to simulate subgrid scale heterogeneities related to elevation, snow depth, frozen soil, lakes, wetlands and vegetation cover. VIC has been used extensively in many parts of the world to simulate the impacts of climate change on snow processes, water resources, erosion, fire risk, availability of water for agriculture and land-atmospheric interactions (Adam et al., 2009; Allen et al., 2015; Barnett et al., 2005; Elsner et al., 2010; Gould et al., 2016; Vano et al., 2010).

3.1.3. CropSyst

CropSyst (Stockle et al., 1994; Stöckle et al., 2003) is a process-based cropping system model that simulates crop development, growth and yield in response to soil, climate and management. CropSyst captures the effects of different factors such as atmospheric CO_2 concentration, water, energy and nutrient availability on biomass production and yield (Stöckle et al., 2003). CropSyst has been evaluated and used for numerous crop types in many parts of the world (e.g., Confalonieri and Bocchi, 2005; Donatelli et al., 1997; Pala et al., 1996; Pannkuk et al., 1998). Although the original resolution of the model was plot-scale, it is applied at different scales (Stöckle et al., 2014). The model has also been implemented in many agricultural research applications and modeling frameworks (Adam et al., 2015; Stöckle et al., 2014). More than 30 types of crops are grown in the Yakima River Basin (see Table 1). Crop growth and phenology are mechanistically simulated through the CropSyst component of the integrated VIC-CropSyst model.

3.2. The irrigation module

We developed an irrigation module for VIC-CropSyst that mechanistically simulates the amount and frequency of irrigation and

Table 1
Examples of different crop groups handled by VIC-CropSyst that occur in the Yakima River Basin.

Crop Group	Examples of Crops Grown in the YRB
1-Cereal grains	Winter and spring wheat, corn, barley, oats
2-Vegetables and melons	Onion, herbs, peppers, asparagus, squash
3-Fruits and nuts	Grape, pear, peaches, apples, cranberry
4-Root crops	Potato
5-Leguminous crops	Green and dry bean
6-Forages	Pasture, alfalfa, hay, grass, clover
7-Oil seeds	Soybean, mustard, sunflower

irrigation losses (Fig. 3). The following sections describe how the irrigation module simulates irrigation processes and losses.

3.2.1. Irrigation scheduling

The irrigation module monitors the soil moisture; when it drops below a certain threshold, it signals the need for irrigation. To avoid water stress, irrigation scheduling is simulated using the following two considerations, depending on which comes first: 1) capacity of irrigation systems which define the maximum amount of irrigation (i.e., soil moisture depletion) in each event, and 2) maximum allowable depletion (MAD), which takes crop-specific sensitivity to dry periods into account. MAD is the fraction of the available soil moisture [field capacity (FC) minus permanent wilting point (PWP)] that can be depleted before the onset of crop water stress. The following inequality determines if the soil moisture is dry enough to trigger irrigation (i.e., an irrigation event is triggered if this becomes true)

$$\left(\sum_{i=1}^{i=N}(\theta_{FC_i} - \theta_i) \times D_i - \sum_{i=0}^{i=N}(\theta_{FC_i} - \theta_{PWP_i}) \times MAD \times D_i\right) > 0 \quad (1)$$

where θ_{FC} is the soil water content at field capacity, θ_{PWP} is the soil water content at permanent wilting point, θ is the soil water content, D is the thickness of layers and N is the number of soil layers occupied by roots. The amount of irrigation (I; mm) needed depends on the type of thresholds used to trigger irrigation and is calculated with Eq. (2):

$$I = \begin{cases} 1 - \sum_{i=1}^{i=N}(\theta_{FC_i} - \theta_i) \times D_i \\ \quad or \\ 2 - Capacity\ of\ Irrigation\ System \end{cases} \quad (2)$$

3.2.2. Irrigation amount

Uniformity and efficiency of an irrigation system play an important role in total water demand and losses. In fields with low uniformity and efficiency, farmers need to apply more water to deliver enough moisture to the root zone. The extra water will increase losses of the irrigation system to deep percolation and runoff. The irrigation amount in VIC-CropSyst is calculated based on soil water deficit, irrigation efficiency and uniformity. Because the efficiency of irrigation systems also depends on total irrigation water, to calculate the applied irrigation amount we used prescribed efficiencies and uniformities which approximate a typical amount of irrigation for each system to ensure minimization of crop water stress. Although the total irrigation water is applied based on the prescribed efficiency, VIC-CropSyst's actual irrigation efficiency is simulated through the mechanistic irrigation module. The prescribed efficiencies are taken from the values suggested by Howell (2003). The prescribed values discussed here can be modified to consider detailed, field-specific information about irrigation management, soil and climate conditions. In VIC-CropSyst, the total amount of irrigation is calculated as:

$$I_t = \frac{I}{E_f \times U} \quad (3)$$

where I_t (mm) is the required irrigation depth, E_f is the prescribed irrigation efficiency, and U is the irrigation uniformity. Uniformity of irrigation depends on many factors such as system characteristics and management, soil type and slope (Clemmens, 1988; Horst et al., 2007), climatic factors such as wind (Playán et al., 2005), and the hydraulic characteristics of a system (Nakayama and Bucks, 1981; Yurdem et al., 2015). In VIC-CropSyst, we prescribe typical uniformity of each system using the ranges suggested by Smajstrla et al. (1988) for surface irrigation; ElWahed et al. (2015), Playán et al. (2006), and Montazar and Sadeghi (2008) for sprinkler and center pivot irrigation; and Yurdem et al. (2015) for drip irrigation. Surface, solid set, drip and center pivots are assumed to have a uniformity of 0.65, 0.80, 0.95 and 0.90, respectively.

3.2.3. Irrigation methods

A total of 10 different irrigation methods from four common types of irrigation systems are included in VIC-CropSyst. The four major categories are 1) surface, 2) center pivot, 3) sprinkler and 4) drip. The data used to characterize irrigation methods in the model were obtained from reports, papers and commercial catalogs (e.g., Nelson Co., 2014; RainBird, 2014). In this study, we selected four irrigation systems to represent each of the categories. Table 2 shows different irrigation system methods and the representative subcategories simulated in this study. We refer to the name of the system categories and sub-categories instead of each representative system throughout the paper. It is also worth mentioning that different irrigation methods have their own distinct impacts on the land surface and its interactions with the aquatic and atmospheric components of the earth system. The fact that VIC-CropSyst distinguishes these differences enables it to capture the feedback process between irrigation systems and water and energy cycles over areas like YRB with diverse irrigation systems.

3.2.4. Evaporation losses

VIC-CropSyst assumes irrigation evaporative losses happen through three main pathways including soil surface, canopy intercepted water and irrigation droplets. The following three sections discuss how these processes are simulated in VIC-CropSyst.

Table 2
Simulated irrigation systems in VIC-CropSyst and loss terms associated with each irrigation system. Ed, Ec and Es are evaporative losses from irrigation droplet, canopy-intercepted water and the wetted area during irrigation, respectively. RO and DP are runoff and deep percolation losses, respectively. "Yes" and "No" indicate whether a loss term is included for each specific irrigation system. Reports and commercial irrigation catalogs (e.g., Nelson Co., 2014; RainBird, 2014) were used to characterize the irrigation systems.

Categories	Sub-Categories	Representative System in this Research	Evaporative Losses			*RO*	*DP*
			E_d	E_c	E_{si}/E_s		
1. Surface	Border	Border	No	No	Yes	Yes	Yes
	Basin		No	No	Yes	Yes	Yes
	Furrow		No	No	Yes	Yes	Yes
2. Center Pivot	Impact	Spray (A3000-Nelson)	Yes	Yes	No	Yes	Yes
	Spray		Yes	Yes	No	Yes	Yes
3. Sprinkler	Solid set	Solid set (R2000WF-6_Nelson)	Yes	Yes	No	Yes	Yes
	Wheel move		Yes	Yes	No	Yes	Yes
	Big gun		Yes	Yes	No	Yes	Yes
4. Drip	Surface	Surface drip	No	No	Yes	Yes	Yes
	Subsurface		No	No	No	No	Yes

3.2.4.1. Soil water evaporation. In surface and drip irrigation, the fraction of the surface that is wet is used to calculate irrigation evaporative losses from soil (E_s). The wetted surface fraction for basin and border systems is 100% and 50%, respectively, for furrow systems. The wetted surface under drip irrigation is calculated with the following equation developed by Malek and Peters (2011):

$$d = q^{0.543} K_s^{0.772} t^{0.419} \Delta\theta^{-0.687} \rho_b^{0.305} \quad (4)$$

where d (cm) is the wetted radius, K_s (cm/h) is the saturated hydraulic conductivity, t (h) is the irrigation duration, $\Delta\theta$ is the change in the soil water content during irrigation and ρ_b (gr/cm^3) is the soil bulk density. The irrigation evaporative losses from center pivot and sprinkler methods include two major components: E_c and E_d.

3.2.4.2. Evaporation from canopy-intercepted water. VIC's original formula is used to estimate evaporation from canopy-intercepted water (E_c), which depends on potential evapotranspiration (ETp; mm) and canopy size. VIC uses the following equation (Liang et al., 1994) to calculate E_c:

$$E_c = ET_p \left(\frac{r_w}{r_w + r_0}\right)\left(\frac{W_i}{W_{im}}\right)^{\frac{2}{3}} \quad (5)$$

where r_w (sec/m) and r_0 (sec/m) are the aerodynamic and architectural resistances, respectively; W_i is the amount of water on the canopy available for evaporation; and W_{im} is the maximum canopy interception calculated from the following relationship:

$$W_{im} = K_L \times LAI \quad (6)$$

where K_L is a constant assumed to be equal to 0.2, according to Dickinson (1984). Because these equations were not originally developed for agricultural fields, they tend to overestimate E_c (Kang et al., 2005). In VIC-CropSyst, we use the following equation by Kang et al. (2005) as the maximum limit to avoid unreasonable E_c (mm) values:

$$E_{cMax} = 0.3681 \times \log(LAI) + 0.2692 \quad (7)$$

3.2.4.3. Droplet evaporation. Relationships proposed to calculate droplet evaporation (E_d) can be categorized into two groups: 1) simple regression equations derived from experiments (e.g., Playán et al., 2005; Frost and Schwalen, 1955) and 2) equations based on energy and water balances. These formulas usually consider changes in the temperature of droplets and buoyancy force in the calculation of droplet energy balance and trajectory (e.g., Carrión et al., 2001; Kincaid and Longley, 1989; Thompson et al., 1986). The first group usually combines the water moved by wind drift with evaporative losses, while in large-scale regional studies, it is a common assumption that wind-blown lateral movement of water droplets between grid cells is negligible. The second group, which differentiates the wind drift and E_d, usually requires many assumptions and simplifications to solve the equations, and many of them work for a single droplet or one sprinkler and therefore are not appropriate over regional scales. In this study, we developed a simple relationship suitable for large-scale modeling.

The following three factors have been considered the most important parameters in E_d simulation (Kincaid and Longley, 1989): 1) reciprocal of the size of irrigation droplets (D; mm), 2) available time for evaporation, which is a function of droplet velocity, trajectory in the air and height of the sprinkler (t; sec) and 3) climatic condition, which is represented by ETp (mm). Using these assumptions, the following equation was used to develop a formula for E_d.

$$E_d = ET_p \times \frac{1}{D}^{\alpha} \times t^{\beta} \quad (8)$$

To calculate the time (t) required to move from nozzle orifice to canopy, the movement equation of a projectile motion can be solved for the known height of nozzles ($Y_0; m$), the height of the canopy ($Y; m$), the initial angle of trajectory (θ) and the initial velocity of the irrigation water ($V_0; m/\text{sec}$) using the formula

$$Y = V_0 t \sin\theta - \frac{1}{2} g t^2 + Y_0 \quad (9)$$

where g is the acceleration of gravity ($\frac{m}{s^2}$). We solved Eq. (9) for the roots of the quadratic equations, and then inserted the analytically solved t into Eq. (8).

To calculate the coefficients of Eq. (8) (α and β), the following experimental formula by Molle et al. (2012) was used. They utilized catch can data collected from experiments using RainBird's 46HW sprinkler. The value of E_d was measured using a comparison of electrical conductivity of the irrigation water and the collected samples from the catch cans. They found that

$$E_d = 2.31 + 7.28 \times R_{std} + 2.28 * VPD - 1.78 \times V \quad (10)$$

where VPD is the vapor pressure deficit (kPa), V is the wind speed ($m\ s^{-1}$) and R_{std} is defined as the ratio of the distance from the sprinkler to the maximum radius of the sprinkler. In this study, we calibrated the coefficients of Eq. (8) against Eq. (10), where we assumed that an average of E_d occurs in the middle of the sprinkler's maximum distance, ($R_{std} = 0.5$). Using this assumption and the climatic data of Pullman (in Washington State, U.S.) with similar climatic conditions to many upstream agricultural areas of the YRB (e.g. Kittitas Irrigation District), the α and β coefficients were calculated to be 0.52 and 1.57, respectively.

$$E_d = ET_p \times \left(\frac{1}{D}\right)^{0.52} \times \left(\frac{V_0 \sin(\theta)}{g} + \frac{\sqrt{V_0^2 \sin^2(\theta) + 2g(Y_0 - Y)}}{g}\right)^{1.57} \quad (11)$$

Table 3 shows some typical types of sprinkler irrigation system characteristics and the model prediction of E_d for these irrigation systems. The results in Table 3 are in agreement with previous experiments and modeling studies. Thompson et al. (1993) suggested a 2% maximum limit of evaporation loss from impact and

Table 3
Implementation of Eq. (11) for some of the irrigation systems available in VIC-CropSyst. System characteristics (H, Cd, Y_0 and D) included in this table are from commercial catalogs.

Type	Group Name from Table 2	Model	Company	Y_0 (m)	D (mm)	t (sec) Eq. (8)	E_d (%) Eq. (11)
CP impact	Center Pivot	30FH/30FWH	RainBird	2.7	1.00	2.93	5.41
CP spray	Center Pivot	A3000	Nelson	1.8	2.01	0.71	0.40
Big gun	Sprinkler	200TB	Nelson	2	2.38	3.61	9.56
Solid set	Sprinkler	R2000WF-6	Nelson	1.00	1.57	1.91	2.18
Moving wheel	Sprinkler	R2000WF-6	Nelson	1.00	1.52	2.39	3.15

spray sprinklers. Lorenzini (2004) and Yan et al. (2010) reported a maximum of 9% and 4.3% loss during sprinkler irrigation, respectively. VIC-CropSyst also provides another option for users to calculate E_d with the following equations (Playán et al., 2005). These equations calculate the combined amount of wind drift and evaporation losses (*WDEL*; %) using air temperature (T; °C), wind speed (U; m/s) and relative humidity (RH).

$$\text{For the sprinkler}: WDEL = 20.3 + 0.214U^2 - 0.00229RH^2 \qquad (12)$$

$$\text{For moving laterals and center pivot}: WDEL = -2.1 + 1.91U^2 + 0.231T \qquad (13)$$

3.2.5. Irrigation runoff losses

In irrigated areas, runoff loss from irrigation occurs when the irrigation application rate (A_r; $\frac{cm}{h}$) is higher than the infiltration rate (f; $\frac{cm}{h}$). In this research, a simplified analytical infiltration equation developed by Philip (1957) was used to calculate infiltration rate:

$$\mathrm{f} = \frac{1}{2}\mathrm{S}t_{irr}^{-0.5} + \mathrm{K_s} \qquad (14)$$

where t_{irr} (not in Eq. (12)) is the duration of irrigation (in hours); S $\left(\frac{cm}{h^{0.5}}\right)$ is the sorptivity, and $A\left(\frac{cm}{h}\right)$ and the recommended value of K_s (Youngs, 1968). Sorptivity was calculated using the method employed by Rawls et al. (1992) and Youngs (1968):

$$S = \sqrt{2(\varnothing - \theta)K_sS_f} \qquad (15)$$

where $\varnothing$ is the soil porosity, θ is the soil water content, K_s is the effective conductivity at saturation $\left(\frac{\mathrm{cm}}{\mathrm{h}}\right)$ and S_f is the effective wetting front suction (cm). S_f depends on soil texture and porosity and is calculated using the formula developed by Rawls and Brakensiek (1989).

3.2.5.1. Irrigation application rate (A_r). The A_r in a well-managed irrigation system usually depends on system characteristics, soil texture and hydraulic conductivity. This means that the application rate has to be calculated for each grid cell independently. Therefore, to approximate a reasonable A_r, VIC-CropSyst estimates the irrigation duration (t_{irr}) using the soil characteristics of each grid cell (Fig. 3). In this calculation, t_{irr} is used to estimate the rotation time in center pivot irrigation, and overlap and layout of sprinklers in solid-set, wheel move and big-gun irrigation systems. Then, approximate irrigation intensity is compared with the irrigation infiltration rate (f) and runoff is calculated.

3.2.6. Deep percolation

Deep percolation of irrigation water can be a significant component of the hydrologic cycle in an irrigated area, especially when the soil is highly permeable and irrigation systems have poor efficiency and uniformity. In VIC-CropSyst, when water moves below the root zone area where it is not reachable by the crop roots, it is considered to be deep percolation loss.

In this setup, VIC-CropSyst includes 17 soil layers; the first 16 layers are 10 cm each, and the depth of the lowest layer is a calibration parameter that varies for each grid cell. Although our model simulates daily root depth and its vertical distribution across the soil layers, we use the maximum root depth for each crop as the threshold below which water is not accessible for crop roots; thus, the percolation of water below this depth becomes an irrigation loss. Maximum root depth is a crop-specific constant (e.g., 180 cm for corn, 150 cm for wheat, and 60 cm for potato).

Note that, while deep percolation and runoff losses are farm-level irrigation losses, they are not losses at the watershed scale; i.e., they are released back into the stream network as return flows and can contribute to downstream irrigation.

3.3. Irrigation losses metrics

3.3.1. Irrigation application efficiency (E_f)

This term is conventionally defined as the fraction of total irrigation water (I_t) that is delivered to the crop root zone (Burt et al., 1997; Howell, 2003; Solomon, 1988). In VIC-CropSyst, Eq. (16) is used to calculate E_f.

$$E_f = 100 \times \left(1 - \frac{E_{si} + E_d + E_c + RO + DP}{I_t}\right) \qquad (16)$$

This value indicates what fraction of total water applied to a field is stored in the root zone. E_f is a farm-scale concept and does not take into account regional implications of deep percolation and runoff losses.

3.3.2. Irrigation transpiration fraction

In this study, we defined an efficiency criterion (i.e., irrigation transpiration fraction, *ITF*) that is the fraction of the total applied irrigation water that is used through crop transpiration (T) and effectively participates in biomass production. To calculate the *ITF*, in addition to conventional irrigation loss terms happening during irrigation, evapotranspiration needs to be partitioned into the irrigation evaporation loss from the top soil when irrigation is not occurring (*ESTS*) and T. Once *ESTS* is calculated, *ITF* can be calculated using Eq. (17).

$$ITF = \left(1 - \frac{ESTS + E_{si} + E_d + E_c + RO + DP}{I_t}\right) \qquad (17)$$

Despite the irrigation application efficiency that is calculated during the irrigation event, ESTS and T happen throughout the irrigation season. This creates a challenge in recognizing whether the origin of the transpired water is precipitation or irrigation, because soil has initial moisture before irrigation and there are usually precipitation events during the irrigation season.

VIC-CropSyst partitions ET into evaporation and transpiration based on the canopy coverage (CC), but because the initial soil moisture before the first irrigation event and precipitation events during the irrigation season also contributes to ET, it is currently infeasible (without particle tracking which is not implemented in VIC-CropSyst) to directly calculate what fraction of irrigation water goes to E_s and T. To estimate ITF, we assumed that the ESTS depends on the water content of the soil top layer (θ_{WC1}), field capacity (θ_{FC}), canopy coverage (*CC*) that partitions the *ESTS* and transpiration, and irrigation-wetted surface (*WS*) as follows.

$$ESTS = (\theta_{WC1} - \theta_{FC}) * CC * WS \qquad (18)$$

3.3.3. Evaporative loss ratio

Evaporative loss ratio (ELR) is defined in this study as the ratio of evaporative losses over non-evaporative losses as follows.

$$ELR = \frac{E_d + E_{si} + E_c}{RO + DP} \qquad (19)$$

The ELR is important in many agricultural regions such as the YRB because an increase in the ELR may be associated with a reduction of water that is returned to the watershed, which may negatively impact downstream water availability and agricultural productivity.

3.4. Simulation protocol

3.4.1. Calibration

VIC-CropSyst was calibrated over the Yakima River Basin using USBR's reconstructed stream flows. Because YRB has many water structures such as dams and reservoirs, and because there are many diversion points that deliver water from the river to irrigation lands, observed streamflow is not comparable with VIC's simulated naturalized flow. The reconstructed flow considers the regional information on operation of water structures and provides an estimate of naturalized flow. Streamflow calibration was done for six USGS stations: Yakima River at Parker, Yakima River at Cle Elum, Kachess River near Easton, Yakima River near Martin, Tieton River near Tieton dam, and Bumping River near Nile. Calibrated parameters include a coefficient that defines the shape of the VIC curve that partitions precipitation into runoff and infiltration (b_i), maximum base flow generation (D_{SMAX}), the fraction of D_{SMAX} where non-linear baseflow begins (D_s), and the fraction of maximum soil moisture where non-linear baseflow occurs (W_s). More details on the calibration process of VIC-CropSyst over the YRB can be found in Malek et al. (2017). The range of calibration parameters are given in Table 4, which also shows the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970), defined as:

$$NS = 1 - \frac{\sum_{t=1}^{T}\left(\widehat{Y}_i^t - Y_o^t\right)^2}{\sum_{t=1}^{T}\left(Y_o^t - \bar{Y}_o\right)^2} \tag{20}$$

where NS is the Nash-Stucliffe coefficient; $\widehat{Y}_i^t$ is simulated flow; Y_o^t is the observed flow; and $\bar{Y}_o$ is the annual average observed flow. The NS coefficient was calculated at daily and monthly time-steps.

3.4.2. Method cross-comparison

VIC-CropSyst's flow simulation was compared against USBR's reconstructed flow for the time period between 1997 and 2010. We have also evaluated simulated irrigation application amount. To do that, we compared the simulated irrigation demands from 1980 to 2010 with USBR's (2010) estimated irrigation demands. USBR estimated irrigation demand using observed diversion, cropping pattern and irrigation efficiencies. As a cross comparison we compared our simulated results for application irrigation efficiency with the estimates of the Food and Agriculture Organization of the United Nations (FAO;1989), Almas et al. (2002), Howell (2003), Solomon (1988) and local information gathered over the YRB by the USBR (2010).

3.4.3. Model application periods

To isolate the climate change trend from seasonal to annual signals (Abatzoglou et al., 2014; Cayan et al., 1999; Miles et al., 2000), we compared averages of irrigation efficiencies over a 30-year historical period (1980–2010) to two future periods of 2030–2060 and 2060–2090.

3.5. Data

The historical gridded climate data used to run the model were developed by Abatzoglou and Brown (2012). The climate data were provided in daily time-steps and included maximum and minimum temperature, wind speed and precipitation. The downscaled output of five GCMs forced by two representative CO_2 concentration pathways (RCPs) was used as meteorological input to the VIC-CropSyst model for future climate simulations. Five GCMs were chosen among a total of 18 GCMs using Brekke et al.'s (2010) GCM selection method. The details of these climate data and downscaling methods are explained by Abatzoglou and Brown (2012). The resolution of the climate data was 1/16th degree. Table 5 shows the details of the model and Representative Concentration Pathways (RCPs; Taylor et al., 2011) used in this study. Soil information inputs to the model were developed using the STATSGO data set (Schwarz and Alexander, 1995). Soil parameters used in the model were the same as those used by Elsner et al. (2010) and Maurer et al. (2002), except that we included clay percentage in our new soil file because VIC-CropSyst has the option to internally generate other soil properties (e.g., hydraulic conductivity, field capacity and bulk density) using clay and sand percentages. We also used Saxton et al.'s (1986) pedo-transfer functions. We used the same crop and irrigation distribution data as Yorgey et al. (2011), which were developed using Washington State Department of Agriculture's (WSDA) agricultural land use data layer.

4. Results

In the following section, we compare the irrigation losses simulated for the historical period with the losses estimated by other researchers. Then, we demonstrate the impact of climate change on irrigation losses (evaporation, runoff and deep percolation), irrigation demand, overall efficiency and consumptive water use.

4.1. Irrigation module method cross-comparison

4.1.1. Simulation of irrigation demand over the YRB

The irrigation module was able to simulate the total irrigation water applied over the YRB within a 5% margin of error (Table 6).

Table 4
VIC's calibrated parameters, including a coefficient that defines the shape of the Variable Infiltration Capacity curve that partitions precipitation into runoff and infiltration (b_i), maximum base flow generation (D_{SMAX}), the fraction of D_{SMAX} where non-linear baseflow begins (D_s) and the fraction of maximum soil moisture where non-linear baseflow occurs (W_s). The last two columns show the monthly and daily Nash and Sutcliffe (1970) coefficients for the Yakima River at Parker gauge.

Calibration Parameters	W_s	D_s	D_{SMAX}	C	b_i	Monthly NS (1997–2010)	Daily NS (1997–2010)
Ranges	0.28–0.95	0.2–0.3	0.1–10	2	0.001–0.3	0.833	0.418

Table 5
A comparison of historical (1980–2010) and future (2030–2090) precipitation and temperature for the 5 GCMs considered in this study; these GCMs were forced with two RCP scenarios (RCP 4.5 and RCP 8.5) to create a total of 10 climate scenarios.

GCM	Citation	Average Change in Temperature (°C)	Average Change in Precipitation (%)
GFDL-ESM2G	(Pacanowski et al., 1991)	2.2	6.1
HadGEM2-ES365	(Collins et al., 2011; Martin et al., 2011)	3.4	0.9
HadGEM2-CC365	(Collins et al., 2011; Martin et al., 2011)	3.2	5.0
INMCM4	(Volodin et al., 2010)	1.6	2.2
CanESM2	(Flato et al., 2000)	3.4	9.4

Table 6
Simulation of total irrigation demand over the Yakima River Basin and six major irrigation districts. The irrigation districts are shown in Fig. 1. The units are in million cubic meters (MCM).

Irrigation Districts	Simulated (MCM)	USBR (2010) (MCM)	Error (%)
Kittitas	189	236	20
Roza	278	257	8
Sunnyside	493	468	5
Wapato	367	497	26
Yakima-Tieton	146	93	58
Kennewick	66	73	9
Total On-Farm Irrigation Demand	1540	1624	5

The simulated irrigation demand was also disaggregated to the YRB's six major irrigation districts. District-level comparison of simulated, recorded and estimated demands reveals a higher level of error. Differences between irrigation district cropping patterns and WSDA cropping patterns used in this study can cause these discrepancies; additionally, USBR (2010) discussed how some of the missing data at the irrigation district level (e.g., climate data over the Yakima-Tieton irrigation district) may have caused errors in their own estimates.

4.1.2. Irrigation losses

Table 7 compares our simulated results with those from other studies for the historical period of 1980–2010. In general the simulated irrigation efficiency falls within the ranges of irrigation efficiencies suggested by FAO (1989), Almas et al. (2002), Howell (2003), Solomon (1988) and USBR (2010) (see Table 8).

4.1.3. Partitioning between different loss terms

To assess the performance of VIC-CropSyst in capturing the irrigation loss partitioning, we compared the simulated evaporative losses ($E_d + E_c + E_{si}$) and non-evaporative losses ($RO + DP$) using estimates from the USBR (2010). The USBR used regional irrigation information and observed return flows to estimate the amount of consumptive and non-consumptive irrigation losses over the YRB. In general, VIC-CropSyst simulates lower evaporative and higher non-evaporative losses over sprinkler-irrigated areas as compared to the USBR (2010)'s estimates. These discrepancies might be explained by imperfections in our model parameterizations or by the fact that, in our simulation, droplets that drift away by wind are considered non-consumptive losses while they are considered an evaporative loss by the USBR. The large-scale nature of VIC-CropSyst justifies our assumption because the drifted droplets may fall within the grid cell. Lack of farm-specific management information and missing processes in the model (e.g., the groundwater component and dynamic land-atmospheric interactions) can also contribute to these discrepancies.

4.1.4. Evaluation of deep percolation loss

Simulation of DP is less certain than the other irrigation loss components because water is difficult to track in the model once it enters the soil and because of a lack of DP measurements for calibration and evaluation purposes. Therefore, to place DP losses in perspective relative to overall surface water availability, we plotted DP against other relevant variables, including the sum of total losses, top-of-the-crop irrigation demand, and observed flow (Fig. 4); these results demonstrate that DP is a relatively minor component.

4.2. Impacts of climate change

4.2.1. Impact of climate change on future irrigation demands

VIC-CropSyst was used to simulate the historical (1980–2010) irrigation demand as well as the demand for two future periods: 2030–2060 and 2060–2090. Although the impacts of climate change on irrigation requirements are spatially heterogeneous, the general trend (Fig. 5) shows that the irrigation demand will increase over the Yakima River Basin (YRB), which is in agreement with the results of other studies (Döll, 2002; Fischer et al., 2007; Wada et al., 2013; Yorgey et al., 2011). Future higher irrigation demand is caused by higher evapotranspiration and changes in the seasonality of precipitation, when summers become warmer, longer and drier due to a higher fraction of winter precipitation (Mote and Salathe, 2010). The simulated irrigation requirements for the RCP4.5 scenarios are generally lower (−1.5% for 2030–2060 and +1.1% for 2060–2090) as compared to the RCP 8.5 simulations (6.9% for 2030–2060 and 11.2% for 2060–2090). The decreasing trend of the RCP 4.5 scenarios is due to higher temperatures that accelerate crop growth and development and cause earlier maturity, which shortens the crop-specific growing season and, therefore, the irrigation season (Asseng et al., 2015; Craufurd and Wheeler, 2009). Higher temperatures also mean that farmers can also plant earlier (Sacks et al., 2010; Rosenzweig and Parry, 1994) when soil moisture is higher, therefore decreasing

Table 7
Comparison of our simulated irrigation application efficiency (%) and estimated efficiencies (%) of each irrigation system. The simulation period is from 1980 to 2010, and efficiencies are averaged over the entire historical period. The average value suggested by Howell (2003) is used to estimate the prescribed irrigation efficiencies.

	Solid Set	Drip	Center Pivot	Surface
Simulated	67.7	87.7	80.5	56.4
Howell (2003)	65–80	70–95	75–90	50–80
Solomon (1988)	70–80	75–90	78–95	70–80
Almas et al. (2002)	–	97	75–90	60
USBR (2010)	75	88	85	65
FAO (Brouwer et al., 1989)	75	90	–	60

Table 8
The percentages of evaporative ($\frac{E_d+E_c+E_{si}}{Total\ Irrigation\ water} \times 100$) and non-evaporative ($\frac{DP+RO}{Total\ Irrigation\ Water} \times 100$) losses from different irrigation systems are presented below. USBR (2010)'s estimate of evaporative losses includes wind drift, while this factor is not considered as part of the evaporative losses in our simulations.

	USBR Evaporative (%)	Simulated Evaporative (%)	USBR Non-evaporative (%)	Simulated Non-evaporative (%)
Surface	5	1.1	30	42.5
Drip	5	5.2	7	7.2
Solid Set	10	4.9	15	27.3
Center Pivot	10	6.9	3	12.7

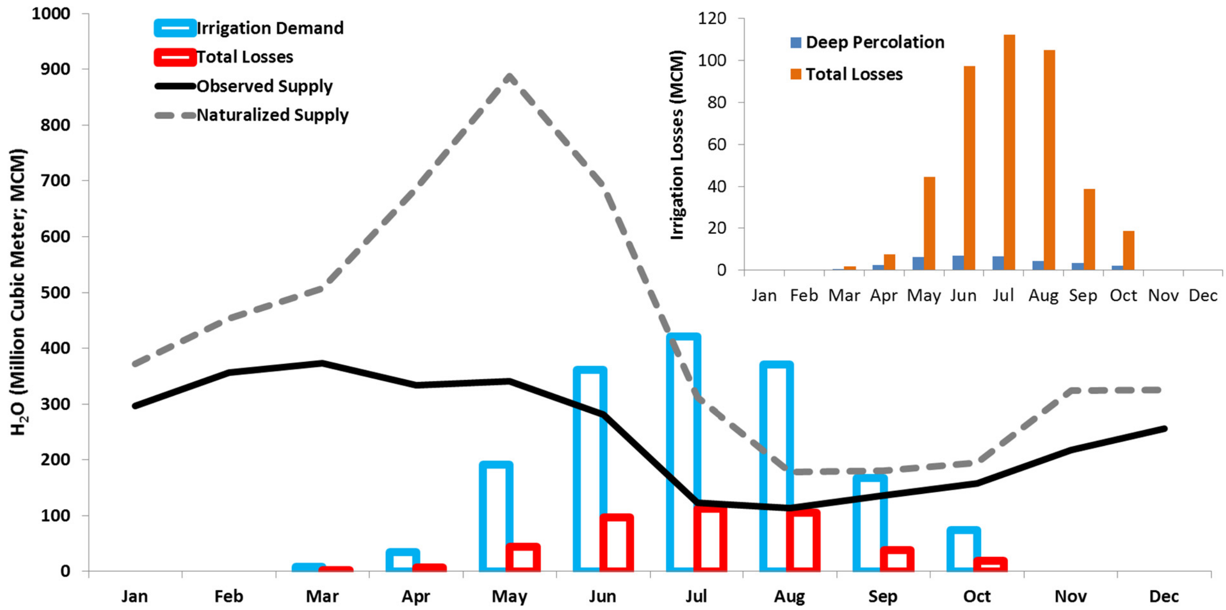

Fig. 4. Comparison of deep percolation (DP) to relevant variables at the outlet of the YRB (the Kiona gage) demonstrates that DP (while highly uncertain) is a minor component. Top right: comparison of DP losses to total losses (Ed + Ec + RO + BF). Main panel: DP and total losses compared to two types of streamflow data: 1) direct measurement of river flow (observed flow) that is highly regulated through complex operation of agricultural and municipal diversions, return flows, and five major dams; and 2) reconstructed naturalized flow (BPA, 2010) that, while not a direct observation, is an estimate of flow in absence of anthropogenic factors such as dams, diversions, and irrigation.

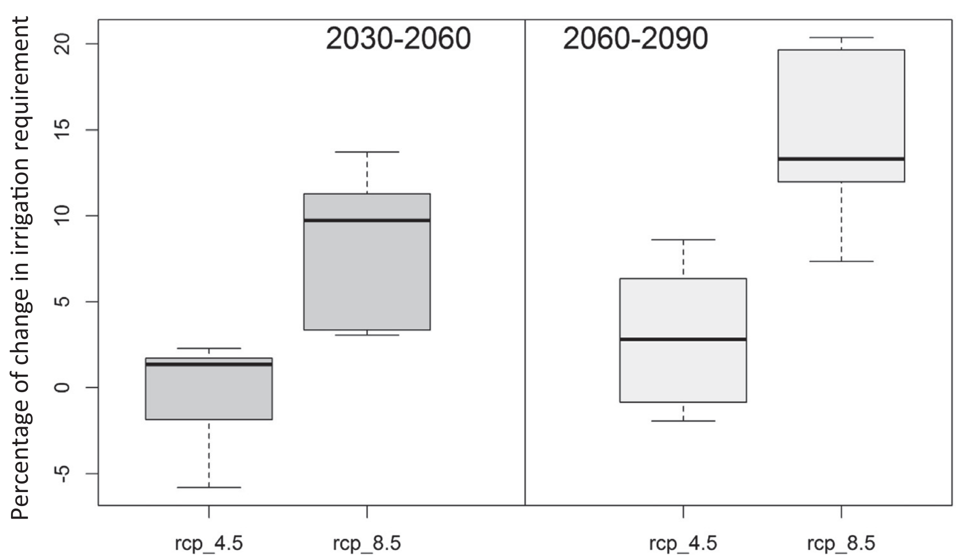

Fig. 5. Impacts of climate change on the irrigation water requirement of crops (including irrigation losses) in the Yakima River Basin. The percentages were calculated by comparing the simulated historical (1980–2010) irrigation demand with the future irrigation demand for two time periods: 2030–2060 and 2060–2090. Each box plot represents one representative concentration pathway (RCPs); RCP 4.5 is associated with a moderate increase in the concentration of greenhouse gases (GHGs), while RCP 8.5 represents more extreme increases.

irrigation demand. Finally, higher CO_2 concentrations decrease canopy conductance which leads to higher water use efficiency and lower water demand (Leakey et al., 2009).

4.2.2. Impact on irrigation losses

We examine the impact of climate change on different irrigation losses, including evaporation from irrigation droplets (E_d), evaporation from soil (E_{si}), evaporation from canopy-intercepted water (E_c), runoff (RO) and deep percolation (DP). We also evaluate the impacts of climate change on the evaporative loss ratio (ELR) and irrigation efficiency.

4.2.2.1. Evaporative losses (E_d, E_{si}, and E_c). VIC-CropSyst was used to simulate evaporative losses over the YRB, and the overall results indicated an increasing trend (in response to climate change) for all of the evaporative loss components (Table 2). The first column in Table 9 shows historical irrigation losses over the entire YRB, and columns 2 and 3 show changes in the irrigation losses for the two future periods. As compared to the historical period (1980–2010), the basin-wide average of E_d shows a 6.5% and 9.4% increase for the 2030–2060 and 2060–2090 periods, respectively, while the simulated E_{si} shows an increase of 4.8% and 6.9% for the same time periods. Increases in temperature and ETp (e.g., Hamlet et al., 2007; Hamlet and Lettenmaier, 1999) are the main

Table 9
Impacts of climate change on the evaporative loss ratio (ELR), future water demand, evaporative losses (E_{si}, E_d and E_c), runoff and deep percolation (%). These values are averaged for all irrigation types over the entire agricultural region of the Yakima River Basin.

Loss Type	Simulated Irrigation Loss (%)—Historical (1980–2010)	Changes in Future Irrigation Loss (%) (2030–2060)		Changes in Future Irrigation Loss (%) (2060–2090)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
DP	4.6	−0.2	−5.3	−2.1	−8.6
RO	20.3	−2.1	−0.8	−2.9	−1.8
E_c	1.5	0.6	0.7	0.8	−0.2
E_d	1.9	6.3	6.7	7.9	10.8
E_{si}	1.3	4.5	5.1	5.6	8.2

drivers of elevated E_d and E_{si}. E_c was also slightly higher for the future periods (0.7% and 0.3%). The reason why the impact of climate change on E_d and E_{si} is more significant as compared to E_c is that elevated ETp is compensated by a higher E_d loss, which leads to E_c reduction. In general, RCP 8.5 represents more extreme scenarios, with a 20% higher change in the future periods as compared to RCP 4.5.

4.2.2.2. Runoff loss (RO). Table 9 shows that future runoff loss decreases for all irrigation systems. This can mainly be explained by the overall increase in the magnitude of evaporative losses (i.e., E_d, E_{si} and E_c), which limits the water that reaches the soil. Therefore, the water available for infiltration decreases, which reduces the runoff losses. Reduction of the water content in the surface soil layer (e.g., Dorigo et al., 2012; Holsten et al., 2009) also contributes to lower runoff losses.

4.2.2.3. Deep percolation loss (DP). The results in Table 9 show a decrease of deep percolation losses in the future climate. An increase in evapotranspiration, which leads to increased evaporative losses from irrigation, is the main driver of the decreasing trend in DP. This is in agreement with other research that suggests a decrease of deep percolation and ground water recharge in a future climate (e.g., Pangle et al., 2014).

4.2.3. Irrigation application efficiency

Irrigation efficiency simulated in this study shows a negligible change when it is averaged over the entire basin (+0.2% for 2030–2060 and +0.4% for 2060–2090). The reason why the efficiency does not significantly change is that the different loss components counteract each other. While the evaporative losses are increasing, there will be less water available for runoff and deep percolation losses.

The impacts of climate change on irrigation efficiency are spatially heterogeneous, and these differences stem from varying soil and climatic characteristics. Although the average efficiency is small over the entire basin, as Fig. 7 shows, efficiency in many parts of the basin will be lower in the future, which could cause further water stress. As a general trend, the negative impacts of climate change on efficiency are higher in the upstream portions of the basin where relative changes in temperature and evapotranspiration are more significant.

The efficiency of drip, center pivot and sprinkler irrigation systems was simulated to be lower in the future, because in these systems evaporative losses are generally higher (and are associated

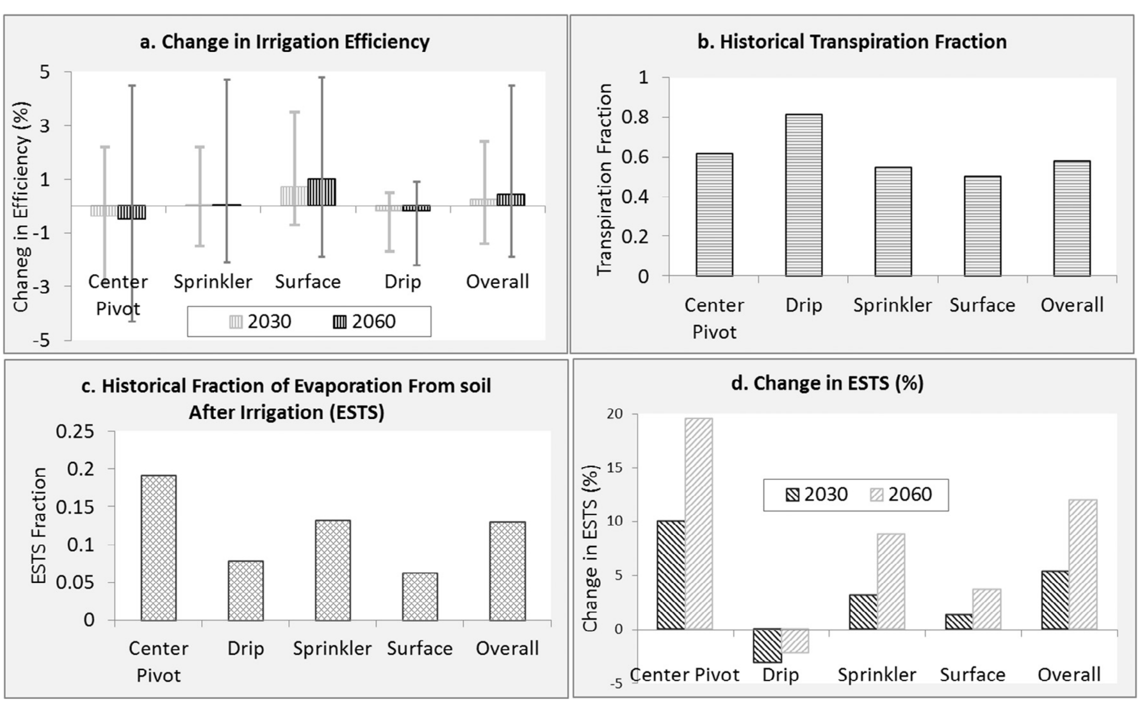

Fig. 6. a) Irrigation efficiency in the historical period and the average basin-wide changes of irrigation efficiency for the two future periods of 2030–2060 and 2060–2090. The bars show that the ranges of efficiency change in different grid cells in the basin and black horizontal lines show the simulated irrigation efficiency. b) Irrigation transpiration fraction. c) The fraction of irrigation water that is lost to evaporation from the top soil layer (ESTS). d) Impact of climate change on ESTS.

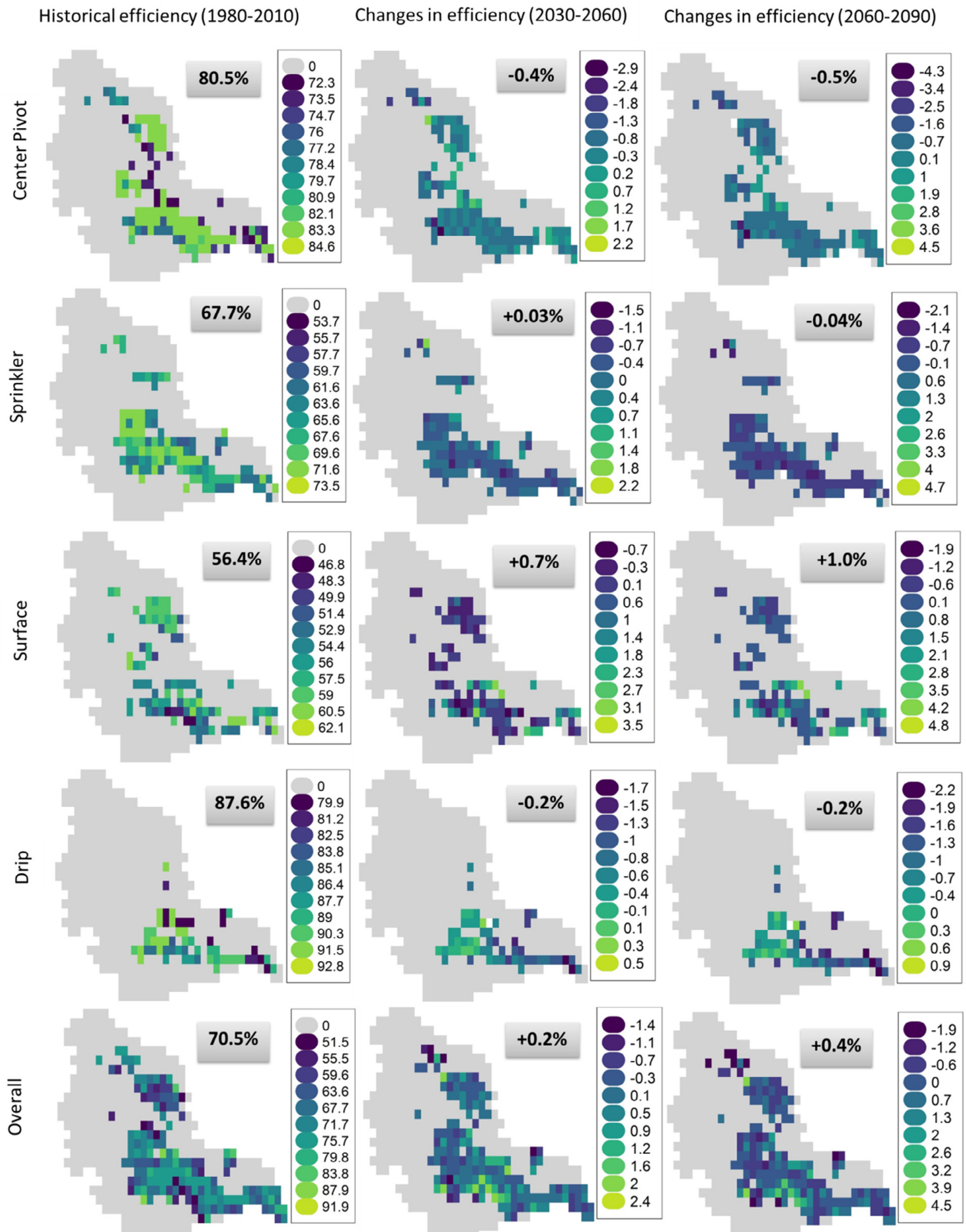

Fig. 7. Impact of climate change on overall irrigation efficiency (E_f) of four irrigation systems. The first column shows E_f for the historical period of 1980–2010, and the second and third columns demonstrate changes in E_f over the two future periods of 2030–2060 and 2060–2090, respectively.

with higher ELRs); therefore, overall efficiency is more significantly affected through increased evaporative losses. In surface irrigation, where non-evaporative losses that occur through runoff and deep percolation dominate other losses, the heightened infiltration processes play a more significant role.

4.2.4. Irrigation transpiration fraction

Simulated ESTS and ITF results are shown in Fig. 6. The results show that drip has the lowest absolute ESTS (Fig. 6c) and highest ITF (Fig. 6b) because the wetted surface is smaller than for other methods considered in this study. Surface irrigation also has a

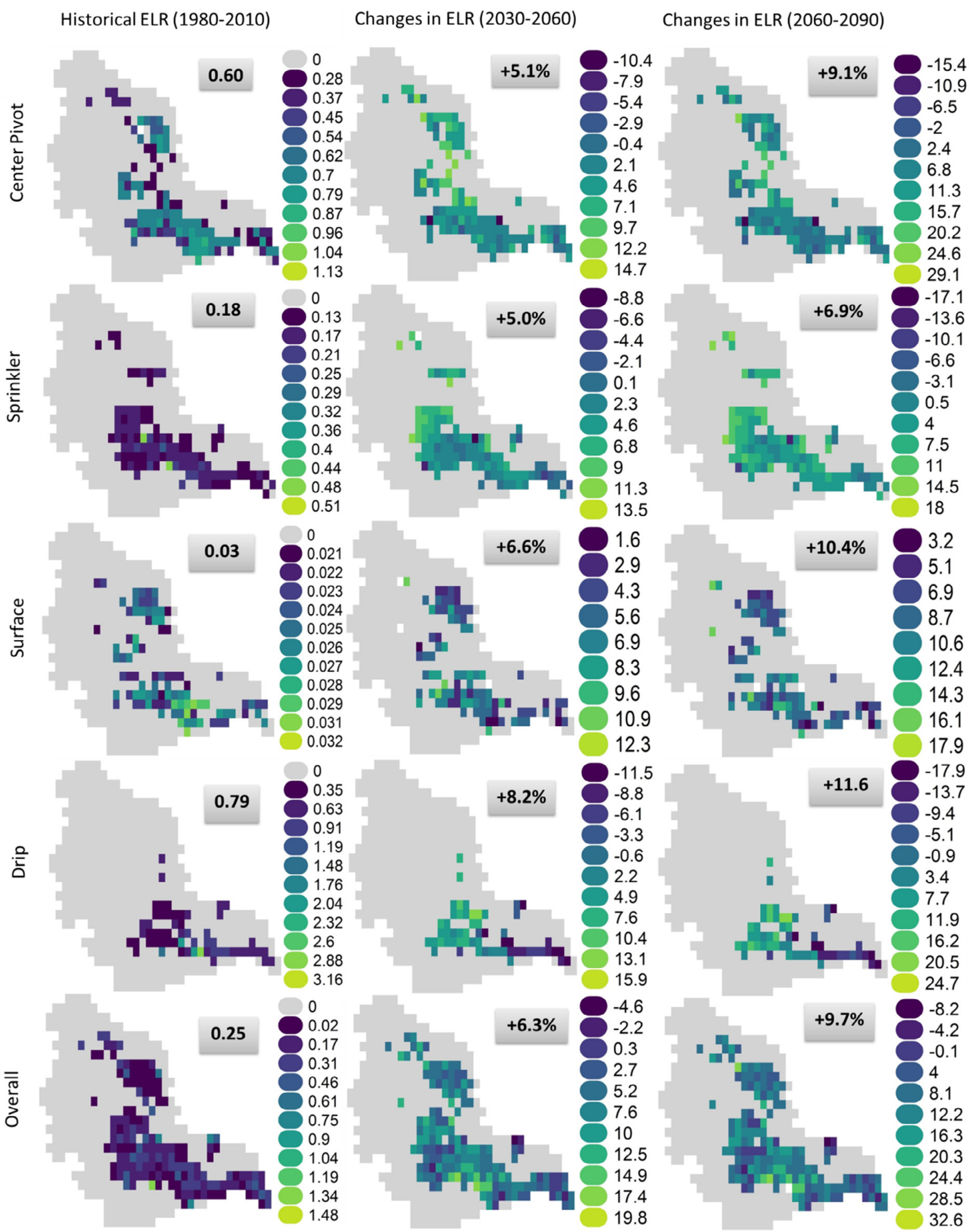

Fig. 8. The impact of climate change on irrigation evaporative loss ratio (ELR) over the YRB. The first column shows the ELR of the historical period (1980–2010), and the second and third columns show changes in the ELR over the two future periods of 2030–2060 and 2060–2090, respectively.

low ESTS fraction because runoff and deep percolation are the dominant loss terms. As Fig. 6d shows, climate change increases the ESTS for all of the irrigation methods except drip irrigation. The reason that drip irrigation's ESTS will be lower in the future is that the canopy fraction increases with higher CO_2 concentration, which cancels out the impact of a higher ET.

4.2.5. Evaporative loss ratio (ELR)

ELR was simulated to be 0.8, 0.6, 0.03 and 0.18 for drip, center pivot, surface and sprinkler systems, respectively (Fig. 8). The overall ELR for the Yakima basin is simulated to be 0.25, which is an average value for all irrigation systems in all of the grid cells. Discrepancies of ELR among different grid cells are caused by

variations in ETp, soil texture and hydraulic conductivity. The simulation of ELR for the future periods of 2030–2060 and 2060–2090 (Fig. 8) indicates that the evaporative loss ratios will increase due to climate change; they will increase by 6.3% and 9.7%, respectively. A higher ELR is caused by the previously discussed increase in the evaporative losses, while runoff and deep percolation will generally decrease.

The impact of climate change on the ELRs of drip irrigation systems is less than that of other systems because the evaporative losses from drip systems do not change significantly. The wetted surface in a drip system depends on the initial water content; when the soil is drier as irrigation begins, it makes infiltration easier and creates a smaller wetted surface, which compensates for the impacts of increasing ETp.

5. Discussion and conclusions

To analyze the future of agricultural productivity, there has been a considerable amount of interest in understanding how climate change impacts agricultural water demand and supply (Döll, 2002; Elsner et al., 2010; Kurukulasuriya and Rosenthal, 2013; Vano et al., 2010). Despite this interest, there is a knowledge gap in our understanding of how water-use efficiency will change in the future as a result of climatic warming. To address this gap, we have incorporated an irrigation module into a hydrological-agricultural modeling framework (VIC-CropSyst). This irrigation module mechanistically simulates the impacts of climate, soil conditions and management decisions on agricultural water processes and losses. The modeling framework can be used to answer research questions related to the impacts of climate change and water management decisions on irrigation losses.

The results of this study show that the future food productivity of water-limited agricultural areas such as the Yakima River Basin (YRB) in Washington State (Vano et al., 2010) may be threatened by a future increase in agricultural water demand. The results also suggest a climate-induced change in irrigation losses, which can be considered from two perspectives: 1) farm-level and 2) watershed-level (Allen et al., 2005; Jensen, 2007). We also discussed how this study can further contribute to the research community under a "broader implications" section.

5.1. Farm-level

While basin-average irrigation efficiency is projected to be slightly higher in the future, the impact of climate change is heterogeneous within the basin. This means that at least some farmers need to apply more water to compensate for less efficient systems in the future. Considering the fact that water resources are currently limited (Vano et al., 2010) and that future increases in ETp are expected to create more irrigation water demand in the region (Chaouche et al., 2010; Douville et al., 2013; Hamlet et al., 2007), a lower efficiency can exacerbate climate change-related threats in comes cases. This can be especially true in basins such as the YRB, where the allocation of water rights are not likely to change based on farm-level demands (USBR, 2002).

The results also show that more efficient irrigation systems (i.e., drip and center pivot) tend to be slightly more susceptible to climate change as compared to surface and sprinkler systems. This suggests the need for further discussion about how selection of an irrigation system impacts the efficiency of water usage in the future, and how informed investment in an irrigation system will consider climate-induced changes in the efficiency of irrigation systems lasting two to three decades. Also, farm-level productivity is affected by the cooling effects of irrigation evaporative losses (Barnston and Schickedanz, 1984; Sacks et al., 2009; Uddin et al., 2013), and because climate change increases evaporative losses, this impact could potentially become more significant in the future.

5.2. Watershed-level

As discussed earlier, many agricultural areas such as the YRB depend greatly on the return flows of upstream farms (Allen et al., 1996; Howell, 2001; USBR, 2012; Willardson, 1985). Therefore, any changes in the partitioning of losses between evaporative (i.e., E_c, E_d, E_{si}) and non-evaporative (i.e., *RO* and *DP*) losses will impact downstream water availability. The results of this study reveal that evaporative losses are expected to increase while runoff and deep percolation losses decrease, reducing the fraction of reusable irrigation losses (Jensen, 2007). This reduction could lead to more significant water stress in the downstream area of the YRB in the future, resulting in potentially large economic consequences. It is worth mentioning that return flow reduction could also lead to degradation of its quality (Bliesner et al., 1977; Causapé et al., 2004; Schmidt and Sherman, 1987); however, quantification of the quality of return flow is beyond the scope of this study.

5.3. Broader implications

We showed that water availability for irrigated areas is potentially affected by changes in the efficiency of irrigation systems and the partitioning of losses (due to changes in return flows). This indicates that the impacts of climate change on agriculture (when captured at the systems, or watershed-scale, level) are more complex than when considering only field-scale changes. Our results also imply the necessity of management strategies that consider possible reductions in return flow. These scenarios may include changes in the timing of agricultural activities (e.g., a decision to double crop which relies heavily on late season irrigation water), strategies in the selection of irrigation systems, and investment in small reservoirs and ponds.

In many important agricultural areas around the world, water availability depends on return flow (e.g., Spain: Causapé et al., 2004; India: Gosain et al., 2005; and Maréchal et al., 2003; Syria: Kattan, 2008; and California: Tanji, 1981). The results of this study reveal that a reduction of non-evaporative losses can potentially reduce downstream water availability, causing regional agricultural productivity to decline. This can also make these regions more vulnerable to droughts and eventually contribute to a less sustainable food supply. Further studies focused on different parts of the world can answer these questions.

Although our modeling framework does not simulate groundwater levels and dynamics, we can infer from our results that climate change-induced changes to DP can contribute to a reduction in groundwater recharge. This issue is particularly important in agricultural regions where water supply relies on groundwater resources and in areas with significant surface-groundwater interactions. This research leads to a better understanding of the effects of climate change on water availability in many agricultural areas where return flow plays an important role in meeting irrigation demands.

Regional irrigation patterns are constantly changing as farmers invest in more efficient systems and alter their irrigation management strategies. Because we aim in this study at teasing out the impacts of climate change on irrigation efficiency, we have not considered changes in irrigation management or technology. Accounting for future shifts in more efficiency technology would result in further reduced runoff and deep percolation losses as compared to historical. For the same reason, we also did not consider changes in future cropping patterns, which would also affect results.

5.4. Summary

Climate change is threatening the availability of surface water during the irrigation season (Elsner et al., 2010; Vano et al., 2010) and it is projected to increase crop water demand. Appropriate water management can improve the sustainability of agricultural productivity in a future climate. Herein, we describe the development and incorporation of a mechanistic irrigation module into a hydrologic/agricultural model (VIC-CropSyst) to study the impact of climate change on future irrigation efficiency and its partitioning between evaporative (which is consumed) and non-evaporative (which returns to the system for downstream users) losses. The results indicate that evaporative losses are expected to increase in the future. Some of these increases are compensated for by a reduction in future deep percolation losses. The overall efficiency of surface, center pivot and solid set irrigation systems will be higher in a future climate, while drip and center pivot systems are expected to operate with slightly lower efficiencies. Also, a general increasing trend in the evaporative loss ratio was observed, suggesting a lower amount of return flow, which can potentially impose an additional threat to water availability during the irrigation season. This indicates the importance of long-term and systems-level planning when selecting and operating irrigation systems.

Acknowledgments

This research was funded by the United States Department of Agriculture (USDA), National Institute of Food and Agriculture (NIFA) Grant Number 2012-67003-19805 (Watershed Integrated Systems Dynamics Modeling; WISDM) and Grant Number 2011-67003-30346 (Biosphere Relevant Earth System Model; BioEarth). This research is also financially supported by Washington State University's Graduate School.

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